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Final IAEA Research Coordination Meeting on "Plasma-interaction Induced Erosion of Fusion Reactor Materials"

October 9-11, 1995, Vienna, Austria

SUMMARY REPORT

Prepared by R.A. Langley

December 1995

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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ABSTRACT

The proceedings and results of the Final IAEA Research Coordination Meeting on "Plasma-interaction Induced Erosion of Fusion Reactor Materials" held on October 9, 10 and 11, 1995 at the IAEA Headquarters in Vienna are briefly described. This report includes a summary of presentations made by the meeting participants, the results of a data survey and needs assessment for the erosion of plasma facing components and in-vessel materials, and recommendations regarding future work.

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1. INTRODUCTION

The final Research Co-ordination Meeting (RCM) on "Plasma-interaction Induced Erosion of Fusion Reactor Materials" held on October 9, 10 and 11, 1995 at the IAEA Headquarters in Vienna was organized as part of the activity within the IAEA Co-ordinated Research Programme (CRP) on the same subject. The main objectives of the Meeting were:

a) to review the progress of the individual projects and existing data on the erosion of plasma facing components in fusion reactors (including internal vessel structural materials and coating materials);
b) to discuss fusion reactor PFC requirements in regards to erosion in the ITER project;
c) to discuss the expected needs of the fusion community beyond ITER;
d) to encourage the early measurement of properties which are deemed most necessary; and
d) to determine the format and content of the final report and external publication.

These objectives were reached during the meeting.

The meeting was attended by eight of the chief scientific investigators of the CRP or their representative, three observers, and the staff of the IAEA Atomic and Molecular (A+M) Data Unit. The List of Meeting Participants is given in Appendix 1.

After opening remarks and adoption of the proposed Agenda, the Meeting proceeded with presentations by each of the participants on experimental and theoretical results pertinent to the CRP subject.

2. BRIEF MEETING PROCEEDINGS

The first day was spent reviewing work preformed by the CRP participants since the last RCM. **Dr. Wolfgang Eckstein** of the Max-Plank-Institut für Plasmaphysik chaired the first scientific session. **Dr. Maria Guseva** of the Scientific Research Centre of the Kurchatov Institute presented the first summary of the work accomplished since the last RCM. She reported on the "Experimental Investigation of the Energy and Temperature Dependence of Beryllium Self-Sputtering". She described the ion source/accelerator for the beryllium ions which had the following parameters: current-25 mA, energy-0.5-10 keV, beam area-12 cm^2. The type of the beryllium studied was a powder-compacted beryllium with about 0.9 wt.% of oxygen, the remainder of the impurities were less than 0.2 wt.%. Experimental data was shown for the erosion of Be-Be at 400 C from 0.5-10 keV. This compared well with the calculated results of Eckstein et al., IPP 9/82, 1993. In addition experimental data was presented for 3 keV Be on Be for temperatures from 370-1070 K. Below 770 K the self-sputtering yield is constant but above 870 K it sharply increases and reaches 1 at a temperature of 1170 K and an energy of 0.9 keV. Comparisons were made with carbon self-sputtering results measured by Roth, JNM 145-147(1987)89. This lead her to the conclusion that the self-sputtering yields of beryllium and carbon show that at temperatures below 770 K and ion energies between 0.2 and 10 keV the self-sputtering yields for beryllium are lower than for carbon. The second presentation was made by **Dr. Luo Zhengming** of the Center for Radiation Physics, Institute of Nuclear Science and Technology, Sichuan Union University. He discussed scaling properties of ion transport using the scaled transport cross section σ_t for $A_1 << A_2$. He stated that the technique could be used for calculation of reflection, particle range profile, damage distribution, ionization and other parameters and produced results with high accuracy and predictability. Data were presented for ion-target-energy combinations $A_1/A_2 < 1/6$ and energies 10 eV-1 MeV for particle reflection, energy reflection, range distribution and sputtering coefficient for various ion-target combinations. The final presentation of the first session was given by **Dr. K. Morita** of the Faculty of Engineering of Nagoya University; his collaborators were B. Tsuchiya, K. Yamamoto, and S. Takamura. The purpose of the study was to establish a concept for the suppression of erosion of carbon materials by thin metal carbide coatings in which the surface is self sustained by segregated carbon atoms supplied by the carbon substrate via segregation and diffusion. In order to test the concept it was necessary to develop a new experimental technique to continuously measure the sputtering yield of the target. This was accomplished using an optical spectroscopy technique developed and tested using the NAGDIS I plasma machine. In order to determine the efficacy of the technique the segregation, dissolution, and diffusion of carbon atoms from the graphite substrate through the TiC coating is required. Preliminary studies were done to confirm this technique and preliminary work indicates positive results. The coatings investigated were TiC and WC and preliminary results were obtained for both.

The second scientific session was chaired by Dr. Morita and the first presentation was made by **Dr. A. Haasz** of The Institute of Aerospace Studies at the University of Toronto. He discussed the erosion of pure and doped graphites and beryllium. He had numerous colleagues involved in the various studies; for the doped graphite work these were A. Chen, J. W. Davis, B. Enweani, and P. Franzen and for the chemical erosion of graphite and physical sputtering of beryllium these were B. Mech, A. Chen, J.W. Davis, and E. Vietzke. For the doped graphites they evaluated the thermal conductivity, chemical erosion and radiation-enhanced sublimation, RES. They made extensive use of sophisticated experimental equipment; for the thermal diffusivity measurements: 40 J neodymium-glass laser and a differential scanning calorimeter, for the chemical erosion and RES: dual-beam ion accelerator and line-of-sight QMS and RGA. The dopants used for graphite were B, Si, Ti, Ni, Al, and W. The samples were well characterized by measuring the dopant concentration versus depth for various treatments. Results for the thermal conductivity were presented for pure graphites (EK98 and undoped CKC reference) as well as several doped graphites(dopants: B, Ti, Si and W). Results for erosion of graphite were obtained for pyrolytic graphite as a base so that the doped graphites could be compared against it. The different mechanisms studied were physical sputtering, chemical sputtering, RES, and thermal sublimation. The materials studied were HPG99, EK98, CKC and the doped graphites where the dopant concentration was varied from 0 to 20%. The major conclusions drawn were that chemical sputtering and RES can be substantially reduced using dopants and that both decrease with increasing dopant concentration. The two most promising dopant elements for reducing erosion are B and Ti. In addition to the above described work the group is currently working on low-energy (down to 10 eV) particle induced erosion for beryllium and carbon materials. They have measured the chemical sputtering yield for deuterium ions from 273 to 1100 K and from 10 to 2000 eV. They have started a study of the synergistic erosion of graphite due to hydrogen ion and oxygen ion bombardment. Initial results have shown release of CO and CO_2 and they presented results for the yield as a function of temperature from 273 to 1800 K. The next presentation was made by **Dr. W. Eckstein** of the IPP Garching. His colleagues in this study were J. Roth, H. Plank and R. Schwoerer. The study consisted of the study of the erosion of Si- and Ti-doped graphites by deuterium irradiation. Specifically they studied chemical erosion mechanisms for pyrolytic graphite and boron doped graphite, USB15, chemical erosion at low fluences for B_4C, SiC, TiC and LS10 with 10at% Si and Ti, and at high fluences preferential erosion and composition changes, evolution of surface topography and erosion yields were studied. A quantitative model was developed for thermal activated chemical erosion and a complete analytic description of carbon erosion by hydrogen was made which included both physical sputtering and physical sputtering of hydrocarbons. They drew the following conclusions: doped graphites can strongly reduce the thermal activated chemical erosion, although sputtering of hydrocarbon precursors at low ion energies is not suppressed, for dopants with high threshold energy surface enrichment leads to suppression of the hydrocarbon physical sputtering, and the fluence for establishing the self-protecting carbide layer increases with grain size (sub-micron grain size of carbide precipitations is desirable). The next presentation was given by **Dr. E. Vietzke** of the Institut für Plasmaphysik, KFA Jülich. His colleagues in this work were V. Philipps, A. Pospieszczyk, A. Refke and the TEXTOR Team and the work dealt mainly with chemical erosion of carbon based plasma facing materials. Experiments were performed both in the lab and in the TEXTOR fusion research device. They reported on both erosion by hydrogen ions and oxygen ions. They presented results on the chemical erosion of B_4C from 300 to 1800 K and from 250 to a few keV and observed BO, CO, CO_2 and B_2O_2 as release products. They stated that there was an urgent need to measure the energy distribution of released products. A plasma diagnostic was developed to study the released products in the TEXTOR device. In addition a diagnostic was developed to make in situ observations of erosion and redeposition of different limiter materials in the TEXTOR device using optical spectroscopy and CCD cameras. **Dr. Y. Hirooka** of the Fusion Research Program at UCSD presented the next talk which discussed erosion of beryllium by deuterium plasma bombardment and the effects of impurities. The work at UCSD is directed to the ITER-R&D effort and consists mainly of and effort to evaluate surface cladding lifetime under ITER normal operation for beryllium and tungsten claddings. This work is being done in conjunction with General Atomic and Argonne National Laboratory where GA will perform in situ fusion plasma experiments in DIII-D and ANL will develop models to predict erosion of PFCs for ITER. Dr. Hirooka presented data for the effective erosion yield for D on Be and D+0.1%O on tungsten. He made estimates for the lifetime of a 5mm divertor wall for ITER with both slotted gaseous and open geometry divertor. In addition they investigated the carbon poisoning effect for both beryllium and tungsten. They state that the key process for carbon poisioning on beryllium is carbon trapping by beryllium. This leads to reduced erosion but increased retention of hydrogen. Future plans include a new Be-handling facility, continuing erosion experiments on plasma-sprayed beryllium, high-flux redeposition experiments with brazed Be on Cu heat sink and using a thermal Be beam and finally compatibility experiments for Be+W+C compounds and measurement of their erosion rates. The final presentation of the session was make by Dr. Hirooka of the work of **Dr. J. Brooks** of Argonne National Laboratory. Dr. Brooks could not attend the meeting due to a previous commitment but he sent a summary of his work which was presented by Dr. Hirooka. Dr. Brooks has developed a model to analyze erosion lifetime, plasma contamination, and tritium retention for ITER PFC's. He is investigating the ITER vertical diverter design for erosion/redeposition and has found that Be may be incompatible with neon seeding, that carbon has high tritium inventory problems, and tungsten has negligible erosion. The use of neon and tungsten does not result in apparent problems due to high neon reflection at the tungsten surface. The results are somewhat speculative and additional analysis is required. He concludes that 1) the erosion/redeposition process is critical to ITER performance, e.g., Be net erosion is ~1/10 gross erosion and erosion/deposition data generation and code validation is a critical need for ITER, 2) net erosion rates for the vertical diverter are an order of magnitude lower than the gas bag design leading to a low predicted core contamination by sputtering and high codeposition of tritium and carbon, 3) plasma radiation seeding may not work with low-Z materials, and 4) work is ongoing in examining critical plasma surface interaction issues.

3. DATA STATUS AND NEEDS

It was recognized by the meeting participants that in order to do definitive experiments and to obtain meaningful results that for the material studied it was very important to specify in as detailed a manner as possible the characteristics of the material since many of the properties needed are very dependent on the specifics of the material such as method of formation, initial starting material, impurity content, grain size, density (porosity), anneal temperature and other possible factors. In order to provide as useful results as possible it is especially pertinent to identify the ITER reference materials. A session was held to discuss the status of the available data and what data was needed. Table 1 was the result of much discussion by the meeting participants. It is an update and revision of a Table from the previous RCM. One typc of material was added, i.e. redeposited and plasma mixed, and data availability for each of the erosion mechanisms was updated with the specific materials noted where possible and new materials within the general categories also noted. In addition there is the need to identify the ITER reference material for tungsten and to study plasma-sprayed beryllium and tungsten. The vanadium alloy, VCr5Ti5, is of particular interest since it is being considered as an in-vessel structural material.

4. CONCLUSIONS AND RECOMMENDATIONS

This Research Coordination Meeting provided the opportunity for the participants to collectively assess the status of data dealing with erosion of fusion reactor plasma facing materials. The participants concluded that considerable data was available for specific materials under specific conditions but that for many of the conditions which will probably be encountered in ITER and other devices, e.g. the divertor chamber, little experimental data exists and theoretical approaches are not, at present, valid to the low energies required. The CRP members agreed to continue experimental measurements and theoretical calculations as their individual programs are funded and to contribute to a planned publication dealing with this subject and including tritium retention and release effects. A schedule, format, contents, and report structure and tentative contributors to the various sections were agreed to as well as the lead authors: this is summarized in Table 2. It was recommended that this effort be carried out as the last report of the CRP and a tentative meeting was planned for the summer of 1996 for final discussion of the publication.

Table 1. Status of Information on Erosion Processes for Plasma-Materials Interaction for a Select Group of Fusion Reactor-Relevant Materials

Materials	Application		Physical Sputtering		Radiation Enhanced Sublimation	Chemical Erosion$^\$$	Thermal Evaporation
	Plasma Facing	Divertor/ Limiter	Calculations	Experiment			
Li	X	X	S	- need data on self-sputtering	N/A	- data needed for effect of impurities (He ash, C, O)	S
Be	X	X	S	S	N/A	- data needed for effect of impurities (He, C, O) $$	S
Carbon-based materials (pure/doped graphites and CFC's)	X	X	S̲	S	- basic understanding, but disagreement between model and experiment - data needed for high flux # - data needed for new doped materials ## - ###	- satisfactory database for pure graphites/CFC's - need data for doped graphites/CFC's ## - data needed for high fluxes,# and energy of released molecules - data needed for impurities - (He, O, C) (some data available for pure graphites)	- need updating of evaporation rates for multi-component materials
Carbides	X	X	S̲	S̲ +	- not observed	- available for B_4C, SiC, TiC - data needed for impurities (He, O, C)	S̲
Mid Z (steels V-alloys)	X		S̲*	- need data for V-alloys^{++} and for grazing angles vs. roughness	N/A	- data needed for effect of impurities (He, C, O)	- need updating of evaporation rates for alloys++
High Z (W, Mo)	X	X	S	- need data for grazing angles vs. roughness	N/A	- data needed for effect of impurities (He, C, O) (some data available for W, WC, WO)	S
Redeposited and plasma mixed	X	X		D/N	D/N	D/N	D/N

S	- satisfactory database	#	- some data to 10^{17} ion/cm^2.s for Ar^+, H^+, and D^+, need data to 10^{19}
S̲	- some data but more work needed	##	- Si(C)+C, Ti(C)+C, B_4C+C, B+C-C, W(C)+C
N/A	- data not applicable	###	- has not been observed in fusion devices to date
D/N	- data needed	$	- includes ion induced (assisted) release of compounds
*	- need data on segregation effects	$$	- includes BeO
+	- B_4C, TiC, SiC, TaC, WC		
++	- V-5Cr-5Ti		

Table 2. Publication Plan for Final Document of CRP

1. Schedule
   Meeting for final discussion of publication
   (Summer 1996)

2. Format
   Data - handbook presentation for ITER (or equivalent) designers; similar to Nucl. Fusion Supplement, Vol. 4 (1993)

3. Contents (general)
   a) Erosion yield data
   b) Retention data (including diffusivity and solubility); materials to be included: Be, C, W and their compounds

4. Report structure — Processes (General / Specific)

- Materials/chapters
  - Erosion
    - Physical sputtering (Experiment & Theoretical)
    - Radiation Enhanced Sublimation
    - Chemical Erosion (including ion induced release of compounds)
    - Thermal evaporation
  - Tritium Retention
    - Retention (trapping)
    - Release
    - Diffusivity/solubility
    - Recombination

5. Content (detailed/chapters)
   (contributors, *=lead contributors)

5.1 Be	*	Y. Hirooka	5.1.1	Pure Be including HIP and LPPS
		W. Eckstein	5.1.2	BeO
		M. Guseva	5.1.3	BeC
		R. Langley	5.1.4	Other
5.2 C	*	A. Haasz	5.2.1	Pure C including pyrolytic, isotopic, films
	*	E. Vietzke	5.2.2	Doped C including B-, Ti-, Si- doped
		M. Guseva	5.2.3	Redeposited C
		W. Eckstein	5.2.4	Other
		R. Langley		
5.3 W	*	W. Eckstein	5.3.1	Pure W including LPPs, CVD, HIP
		K. Morita	5.3.2	WO
		Y. Hirooka	5.3.3	WC
			5.3.4	Other

5.4 Back-up materials; e.g. Li, V5Cr5Ti, other

6. Responsibilities for chapter contributors
   6.1 Collection of data
   6.2 Formulation of comments/remarks with statement of completeness
   6.3 Critical assessment of data
   6.4 Consideration of uncertainty (accuracy)

Appendix 1

Final RCM: Plasma-interaction Induced Erosion of Fusion Reactor Materials

October 9 to 11, 1995, IAEA Headquarters, Vienna, Austria

LIST OF MEETING PARTICIPANTS

Dr. A.A. Haasz	Institute for Aerospace Studies, University of Toronto, 4925 Dufferin St., Downsview, Ontario, CANADA, M3H 5T6
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Dr. Luo Zhengming	Center for Radiation Physics, Inst. of Nuclear Science & Technology, Sichuan Union University, Chengdu 610064, CHINA
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Appendix 2

Final RCM: Plasma-interaction Induced Erosion of Fusion Reactor Materials
October 9 to 11, 1995, IAEA Headquarters, Vienna, Austria

MEETING AGENDA

Monday, October 9, 1995 **Meeting Room: C07-43**

09:30	Opening Address Adoption of Agenda	
Session 1:	Participant Presentations I	
	Chairman:	Eckstein
10:00 - 10:30:	Guseva:	Experimental Investigation of the Energy and Temperature Dependence of Beryllium Self Sputtering
10:30 - 11:00:	Luo Zhengming:	An Analytical Formula for the Reflection Coefficients of Maxwell Ions with Temperature T and the Dependence of Ion Sputtering Yields on Incident Angles
11:00 - 11:30:	Coffee Break	
11:30 - 12:00:	Morita:	Temperature Dependence of Metal Sputtering Yield from Metal-Carbon Composite Materials under High Heat Flux Plasma Irradiation
12:00 - 14:00	Lunch	
Session 2:	Participant Presentation II	
	Chairman:	Morita
14:00 - 14:30:	Haasz:	Erosion of Pure and Doped Graphites
14:30 - 15:00:	Eckstein:	Erosion of B, Si and Ti Doped Graphites Due to Deuterium Irradiation
15:00 - 15:30:	Vietzke:	Chemical Erosion Behavior of Carbon Based Plasma Facing Materials
15:30 - 16:00:	Coffee Break	
16:00 - 16:30:	Hirooka:	Erosion of Beryllium by Deuterium Plasma Bombardment and the Effect of Impurities
16:30 - 17:00:	Brooks:	(presented by Hirooka)

Tuesday, October 10, 1995

Session 3: Discussion I

Chairman: Hirooka

09:30 - 10:30: Discussion of Status of Erosion of PFC

10:30 - 11:00: Coffee Break

11:00 - 12:30: Discussion Continued

12:30 - 14:00: Lunch

Session 4: Discussion II

Chairman: Vietzke

14:00 - 15:30: Discussion of Future Needs

15:30 - 16:00: Coffee Break

16:00 - 17:30: Discussion Continued

Wednesday, October 11, 1995

Session 5: Discussion III

Chairman: Langley

09:30 - 10:30: Discussion and Preparation of Final Report

10:30 - 11:00: Coffee Break

11:00 - 12:30: Discussion and Preparation Continued

12:30 - 14:00: Lunch

Session 6: Discussion IV

Chairman: Langley

14:00 - 15:30: Discussion of Publication

15:30 - 16:00: Coffee Break

16:00 - 17:30: Discussion Continued

Adjournment of the Meeting

CRP Participants Final Reports

A Summary Report
of the Institute of Nuclear Fusion RRC "Kurchatove Institute" on the coordinated research program on the Plasma–Interaction Induced Erosion of fusion reactor materials

Period: May 1990 – October 1995

Maria Guseva

1. Introduction

Beryllium and carbon-based materials are considered as plasma facing materials. Critical issues for using carbon based materials in ITER include:

- high chemical erosion
- high erosion due to radiation-enhaced sublimation at high temperature.

The possibility suppression of chemical erosion by hydrogen ions was demonstrated the first time on the B-doped graphite USB-15 and alloy C+SiC [1-5]. In accordance with this, we have studied different varieties of graphites and C-C composites doped with B, Ti and Si. For comparison we used pure graphite MPG-8. The following studies were done:

- measurement of temperature dependence of sputtering yield by H^+-ions in the temperature range 200-1600^{0}C;
- test of the Tokamak T-10 rail limiter, consisting of several tiles made of USB-15, B_4C and MG8;
- erosion rate of different doped graphites in plasma disruption simulation experiments by pulsed high power plasma.

At the last CRP meeting in 1993 has been pointed that experimental data for beryllium self-sputtering yields is absent. Since the last CRP meeting the emphasis in the plasma-interaction induced erosion research at our Institute has been shifted from carbon-based materials to beryllium, because at present the carbon-based materials data base is relatively well established.

The major difficulty of the experimental beryllium self-sputtering investigation is the problem of Be-ion generation. The energy and temperature dependence of beryllium self-sputtering yields was measured.

2. Experiment

1. Erosion experiments

Due to Parameters	H^+			Be^+
	Ion beam	Pulsed plasma	Steady state plasma	Ion beam
Ion energy, keV	6,10	1	0,15	0,5-10
Ion flux, cm^{-2} s^{-1}	$1{,}2\times10^{16}$	4×10^{20}	$5\times10^{18}\div2\times10^{19}$	$1{,}5\times10^{16}$
Plasma density, cm^{-3}			$0{,}5\times10^{12}\div10^{13}$	
Electron temperature, eV			20-50	
Power flux intensity, MW/m^2		2×10^3	5 - in ohmic discharge 20 - with ECR heating	
Energy flux density, MJ/m^2		0,12		
Pulse duration, ms		0,06	$500\div1000$ ($100\div400$ during ECR heating)	
Number of pulses		100	2500	
Facilities	accelerator with mass-analyzer for all elements ILU	coaxial accelerator MK-200	Tokamak T-10	180^0-implanter
Remarks			ohmic discharge including some hundreds of shots with disruptions	

2. **Materials tested by the temperature dependences of sputtering yields:** B_4C; graphite USB-15 (doped with B), RGTi (doped with Ti), RGTi+1%B; C-C composite - KUP VM (doped with Si and Ti), KP-5415 (doped with Si,Ti and B), UAM, UAM+1%B; Be - TShP.

   Materials tested by simulation studies of plasma disruptions: graphite - USB-15, Recbor (B doped graphite), POCO-AXF-5Q, Rectim (Ti doped graphite), MPJ; B doped C-C composite - Armir, UAM.

   Vanadium alloys: V6Cr3Fe0,05Zr; V5Cr0,05Zr; V5Mo0,05Zr; V2,5Fe2,5Mo0,05Zr; V1Hf1Cr.

   Titanium alloys: Ti-V-Cr.

The investigated T-10 rail limiter consisted of following carbon and boron-carbon materials: USB-15 coating (100-300 μm) on MPG-8 graphite, B_4C coating (100μm) on MPG-8 graphite and on pyrolitic graphite, MPG-8 graphite.

Plasma- and ion beam- irradiated surfaces were analyzed with Auger electron spectroscopy, X-ray and scanning electron microscope. The sputtering yield was determined by the weight change method with an accuracy 1 μg.

3. Results

I. Chemical Erosion and Radiation–Enhanced Sublimation of Graphite and Carbon/Carbon Composites.

1. Investigation of the temperature dependence of sputtering yield for the different graphites and C-C composite by H^+-ions with the energy 10 keV shows that in accordance with previous results in the B-doped carbon-based materials [1-7] the chemical sputtering is significantly suppressed. The maximum of the sputtering yield including doped with 0,5%B C-C composite UAM shifted to a lower temperature in comparison with the pure graphites.
2. Confirmed with our first [4,7] and Vietzke [8] measurements for USB-15 the process of radiation-enhanced sublimation for B-doped carbon-based materials shift to a higher temperature except C-C composite doped with B (UAM) and with Ti and Si (KUP VM). Probably, the reason is the undoped fibres (only the matrix was doped with B in C-C composite).

II. Studies of Plasma Disruptions by Simulation.

1. The boron-doped graphites are the most structurally-stable and resistive to erosion out of the number of the graphites under study, particularly, if the thermal treatment of B-doped carbon materials before high power pulsed plasma irradiation at high temperature (2300 K for USB-15) is performed.
2. On the B and Ti-doped graphites surface, irradiated with the hydrogen high power pulsed plasma fluxes, the bulges were observed, caused by the melting of B_4C and TiC-phases. Cracks were not detected in these materials. Many microcracks were observed on the undoped graphite surfaces (POCO, MPG) under similar condition. For this materials the main mechanism of erosion is the brittle destruction.
3. Under an effect of the intense pulsed plasma flux on the pure vanadium and vanadium alloys cracks and exfoliations of the surfaces, the melting of the part of the surface and crumbling of some grain were observed .

III. Erosion during Plasma Exposure.

1. No cracks or flakes, which are typical for pure graphites (POCO, MPG-8), on the T-10 boron containing (USB-15, B_4C) limiter tiles on the ion-side were observed.
2. A significant change of the structure of B_4C coating on MPG-8 was observed on the electron side: melting of the layer surface with followed recrystallization. The melting of B_4C covering on the pyrolytic graphite had a single island character. The structure of USB-covering after exposure has practically not changed.
3. Traces of unipolar arcs on the ion side were observed on all tiles and their intensity was larger for the B_4C coverings.

IV. Studies of Beryllium Self–Sputtering(Agency Research Contract No.7917/RB)

1. The energy dependence of beryllium self-sputtering yield in the energy range (0,5-10) keV was measured at 400^0 C for normal incidence. The experimental data for Be self-sputtering yield as function of ion energy agrees well with that calculated by W. Eckstein [9].
2. The temperature dependence of S_s in the temperature range $(100\text{-}900)^0$C was obtained for 0,9 keV Be^+-ions. Below 500^0C the self-sputtering yield of Be is not changed and sharply increases at temperature above 600^0C, attaining the value of 1 at./ion at temperature about 900^0C.

Comparison of the experimental data for Be-Be^+ and C-C^+ [3] shows that “carbon catastrophe” ($S_S = 1$ at./ion) takes place at higher temperature (≥1200^{0}C) than “beryllium catastrophe” (900^{0}C). Then we can conclude that from the viewpoint of operating temperature carbon as plasma-facing material has an advantage in comparison with beryllium.

3. Estimation of lifetime for the Be-divertor, taking account the Be self-sputtering data, was done.

4. FUTURE WORK

1. Effect of angle of ion incidence on the Be self-sputtering yield.
2. Effect of angle of ion incidence on the sputtering yield of beryllium, irradiated by monoenergetic D^+ and He^+ -ions at low energies (at 30 eV).
3. Study of the energy dependence of the Be sputtering yield at irradiation of monoenergetic D^+ -ions for beryllium near-threshold energies (10-200 eV).
4. Beryllium redeposition experiments for producing redeposited samples, including Be-C mixing layer, for investigation of sputtering.
5. Study of self-sputtering yield of Be redeposited films.
6. Study of sputtering yield of Be-C mixing layer, irradiated by Be^+-ions.
7. Study of the threshold energy of W irradiated by D^+-ions.

References

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THE FINAL REPORT FOR RESEARCH CONTRACT NO.5738/RB
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Application of Improved Bipartition Model of Ion Transport to Calculate Light Ion Reflection and Radiation Damage for Fusion Technology

Part of Coordinated Programme: Plasma-Interaction Induced Erosion of Fusion Reactor Materials

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1. INTRODUCTION

The collaboration with IAEA commenced in 1990. In that year, IAEA agreed to fund our Research Contract Proposal (RCP) entitled 'Application of Improved Bipartition Model of Ion Transport to Calculate Light Ion Reflection and Radiation Damage for Fusion Technology'. In the year followed, the Contract became a part of Coordinated Research Proposal (CRP): Plasma-Interaction Induced Erosion of Fusion Reactor Materials. In order to meet the needs of CRP, we presented a new sputtering theory based on the bipartition model in 1993. Finacially aided by IAEA, three important progresses have been made during 1990-1995: 1). Improving the precision of the bipartition model to make it more reliable, especially for the case of M_1(ion mass)$\lesssim M_2$ (target atom mass). 2). Presenting a complete transport theory for sputtering phenomena. 3). Finding the excellent single-parameter correspondence of the light-ion transport, i.e. σ_t-scaling. σ_t is the scaled transport cross section of ion with initial energy, it equals the product of ion pathlength with the macroscopic transport cross section.

2. CALCULATION OF LIGHT-ION REFLECTION

At first stage of carrying out the RCP, our research work is the calculations of reflection coefficients of *H, He* ions and their isotopes by using bipartition model. Before we took part in RCP, the bipartition model had shown its large potential of describing ion transport by winning great success in the calculations of electron transport and preliminary success in the calculations of light-ion transport. Aided financially by IAEA, we have made considerable progresses in ion transport theory since 1990. In the initial stage (1990-1991), we improved the original bipartition model for light-ion transport by using accurate elastic scattering cross section and electronic stopping cross section to take the place of power function appproximation to these cross section, then increased the calculational precision of light-ion transport. During this period, we worked out PANDA-U90 code and used it to calculate the particle reflection coefficients, the energy reflection coefficient and the reflected ion spectra for $H, D, T, {}^3He, {}^4He$ ions with energies from 0.01 KeV to 100 KeV on Be, B, C, Al, Si, Ti, Ni, Fe, Cu, Mo, W, Au at the incident angles as 0°, 15°, 30°, 45°, 60°, 75°. During the period from 1990 to 1992, we modified

PANDA-U90 code to consider the influence of surface barrier upon ion transport (including reflection), and gave out the particle and energy reflection coefficients, on which the influence of surface barrier has been considered in above mentioned parameter range. According to the systematic comparisons between our results and the relevant experimental and Monte Carlo simulation data, which were made by us, as well as by Thomas, Janev and Smith of IAEA[3,4], we may *obtain following conclusions:* 1). When $\mu=M_1/M_2<0.1$, the ion transport behavior may be described very well by CSDA (continuous slowing down approximation), and bipartition model based on CSDA can calculate reflection coefficients and other transport quantities with considerable reliability and high computational efficiency. 2). When $\mu=M_1/M_2>0.1$, the validity of CSDA decreases with the increase of μ. A typical result, the energy reflection coefficient of *He* ion from the Aluminium target has shown in Fig.1. We know that actually there are very few reflected ions which are able to appear in the high energy range, for ions with large deflection angle will lose large amount of energy when $M_1 \lesssim M_2$, while CSDA appoximation can not describe such angular correlation of energy transfer. For this case of $M_1 \lesssim M_2$, the correlation between energy transfer and scattering angle in the elastic collision events must be considered. In order to describe *the angular correlation of energy transfer in our transport* calculation, an important step of our research work in 1993 is the application of characteristic line method to solve the Pn-approximation equations for diffusion ions. The characterestic line method may be proved to be equivalent to Lax-Wendroff scheme with second precision under CSDA, but it can also deal with the angular correlation of energy tranfer in elastic scattering events, while the Lax-Wendroff scheme can not. Now we have finished the programming work for solving the Pn-approximation equations by using characterestic line method. Therefore, we can extend the reflection calculation to the case of multicomponent targets of low Z and give out the accurate particle and energy reflection coefficients for *H, D, T, He* on Be. B, C. Al. Ti, SiC and TiC. The comparison of our recent calculations with existing data shows that bipartition model can be successfully used to the case of $M_1/M_2<1$ due to consideration of the angular correlation of ion energy transfer by means of characteristic line method. In Fig.1 the dark triangle is the energy reflection coefficient ^4He ion from Al, with using PANDA-U94, these results match those accurately calculated by Monte-Carlo simulation. Based on these progresses, in March 1995 we submitted a 2nd set of data *for particleand energy reflection coefficients for H, He* and their isotopes on Be, B, C, Al, Si, Ti, Fe, Cu, Mo, W, Au. Although this set is not yet our recommendation data set, it has shown higher precision in calculation and better agreements with Monte Carlo results than our first set of reflection data completed in 1991, especially for the case of $M_1 \lesssim M_2$.

3. CALCULATION FOR SPUTTERING YIELDS

CPR of IAEA has close relations with erosion problem of fusion reactor material, therefore physical sputtering is one of the greatly considered contents. A quantitative analytic theory with high computational efficiency is still needed. Historically Sigmund proposed a reasonable model for the sputtering[5] . This model has been used in Monte Carlo simulation[6]. Sigmund's theory build itself on the LSS transport theory. However the LSS theory is not appropriate for handling the transport problem with surface and interface. Therefore Sigmund theory is semiquantitative. Viewing the sputtering phenomena from the point of view of transport theory, two problems must be solved. One is how to accurately calculate the distribution function of primary incident particles at the surface, which determines the source intensity of cascade atoms. The other is how to determine the boundary conditions for a barrier surface. The bipartition model can solve these problems[7]. An outline of the new sputtering theory based on the bipartition model was reported in the 1st CRP meeting in 1991. In the second CRP meeting in 1993, we presented the preliminary results for calculating sputtering yields of Carbon and Nickle targets bombarded by *H, D, T, He* ions. In the final CRP meeting we reported the angular dependence of sputtering yields bombarded by *H, D, T*. Fig. 2 shows the angular dependence of sputtering yields by H^+ bombardment to Cu. As an example, we notice that the sputtering theory based on bipartition model can give reasonable sputtering yields and reasonable angular dependence. However generally speaking, our calculation shows weaker angular dependence of sputtering yields compared with Monte Carlo simulation. In the other hand, compared with experimental results, the calculation of threshold behavior should be improved further. Therefore we may say the frame of sputtering theory is reasonable, but theoretical details need to be improved. Because of the high calculation efficiency (for example, the typical computation time of sputtering calculation for a ion-energy-target combination is about 30 seconds by using a 486 PC machine), we intend to put the theory forward and then widely calculate sputtering yields in order to establish systematic sputttering yields data.

4 . THE STUDY OF SCALING BEHAVIOR IN LIGHT ION TRANSPORT

The need of finding out simple and accurate describing method of reflection coefficient causes a further study on scaling behavior of light ion transport. The concentrated study on the scaling properties of light ions has been carried out since 1993. We did a meticulous transport calculation of 3312 different ion-energy-target combinations by PANDA-U93, of which the results confirmed the prediction we made before, i.e. the transport of light ion has an excellent σ_t-scaling. Furthermore, it has verified that the σ_t-scaling as such is not only applied to particle reflection coefficient, but also can be used for energy reflection coefficient, range distribution, ionization and damage distribution[8-12]. The σ_t-scaling of light ion transport, therefore, must be the characteristic of light ion transport. It has also been noted that, generally, the σ_t-scaling is more suitable for describing the features of ion transport than the reduced energy, i.e. ε-scaling. On the basis of this large scale calculations, we have obtained the universal formulas for the particle reflection coefficients, energy reflection coefficients and range distributions, the precision of these formulas can almost match that of Monte Carlo simulation, or the sound analytic transport calculation. We believe they may be used to plasma modelling. The newly achived result is the using σ_t-scaling formula of reflection coefficient to work a simple formula of reflection coefficient of *D, T* ions with Maxwell distribution at the temperature T. We reported the result in the final CRP meeting.

5. CONCLUSIONS

With the aid of IAEA, NNSFC (National Natural Science Foundation of China) and NIFC (Nuclear Industry Foundation of China), great progress has been made in the bipartition theory of ion transport. At present time, the precision of this theory can match that of the fine Monte Carlo codes. In some cases, the different computational results between two algorithms may not come from these methods themself, but come from the different input parameters. A typical example is that the different low-energy behavious of ion reflection coefficients predicted by bipartition model and TRIM code can be attributed the different input data. The former uses Lindhard electronic stopping power, and the later uses Oen-Robinson stopping power which becomes very small for low energy ions, and the ion pathlength increases largely, that causes reflection coefficient increase.

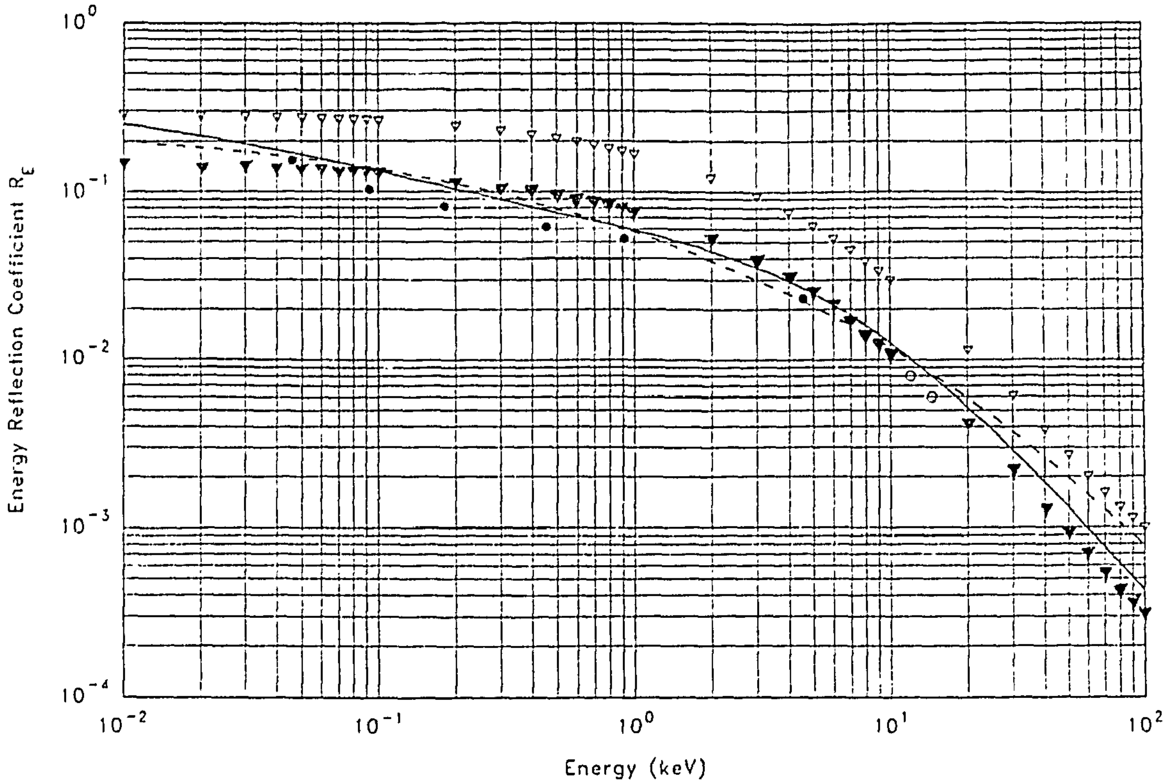

Fig.1. Energy reflection coefficient Re for He^++ Al shown as a function of initial energy. The solid line is given by Thomas, Janev and Smith. The dashed line is given by Itoh. ●, the MARLOWE data. ○, the experimental data by Hildebrand and Manns. ∇, the calculation results by PANDA-91 code. ▼, the improved calculation by PANDA-94 code.

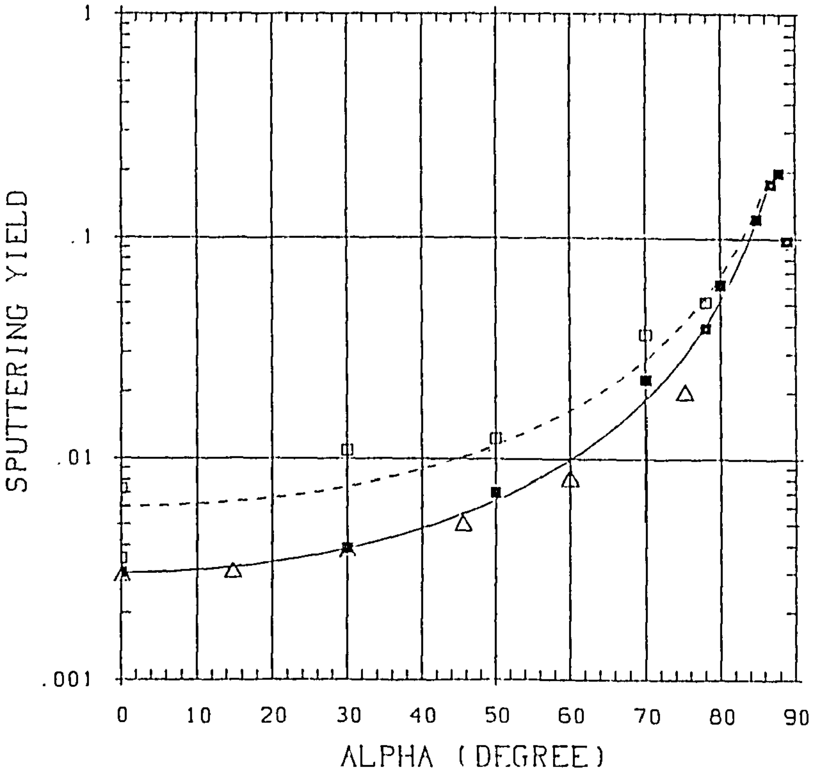

Fig.2. Angular dependence of sputtering yield on the incident angles (ALPHA). □, the experimental data. ■, the calculation results given by TRIM code. Δ, the calculation results given by bipartition model.

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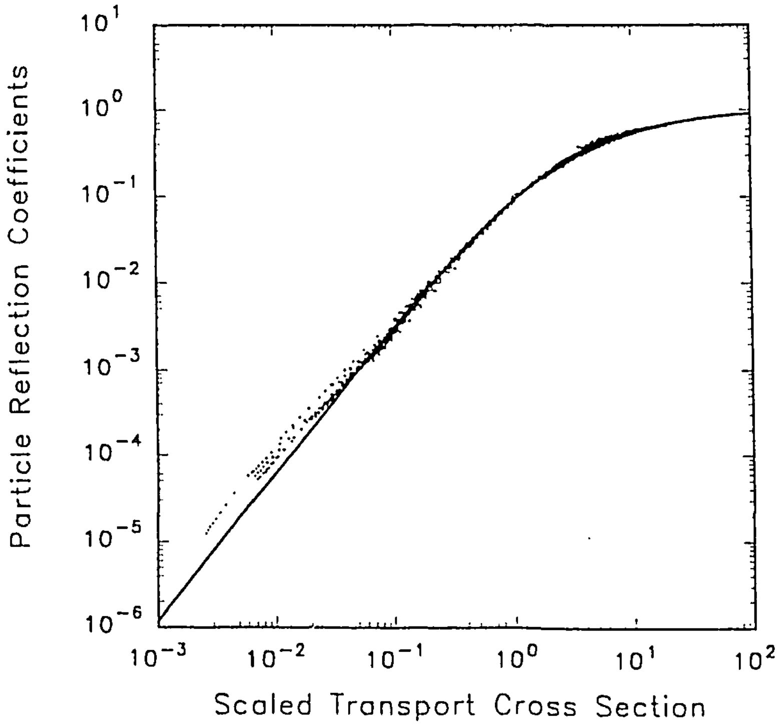

Fig.3. The particle reflection coefficient as a function of the scaled transport cross section. The particle coefficients for 3312 ion-energy-target combinations are calculated by using PANDA-U93 code. The excellent single-value correspondence of reflection coefficient to σ_t has shown in the figure.

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A Summary Report on the Contribution of Nagoya University to the IAEA CRP on "Plasma-interaction Induced Erosion of Fusion Reactor Materials"

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OBJECTIVES of this project are understanding of erosion processes of metal-carbon composit materials including redeposited layer and establishment of the data base and the simulation model for the prediction of the erosion rate and also understanding of re-emission processes of hydrogen isotopes (H and D) in carbon and carbon-metal composit materials and establishment of the data base and the simulation model for prediction of hydrogen recycling rate and hydrogen inventory.

So Far, it has been shown by the present group, concerning the reduction of enhanced erosion of carbon that ion-bombardment induced sputtering of metal from the metal carbide layer deposited on graphite at high temperatures is substantially suppressed by self-sustaining coverage of the surface with segregated carbon atoms, which are supplied via diffusion from the graphite substrate, below certain critical ion flux, for instance, 1×10^{15}keV H^+ $cm^{-2}s^{-1}$ for TiC/graphite at 900°C.

In the first three (1990, 1991, 1992) years, it has been found for WC layer deposited graphite that the sputtering yield of W against the 5 keV Ar^+ bombardment at 1550°C degreases down to zero at a critical ion flux of $4.6\times10^{13}cm^{-2}s^{-1}$ with decreasing ion flux and also that the sputtering yield of W at $6.0\times10^{13}cm^{-2}s^{-1}$ decreases down to zero at a critical temperature of 1500°C with increasing the temperature. The critical ion flux of $6.0\times10^{13}cm^{-2}s^{-1}$ for 5 keV Ar^+ at 1500°C is estimated to correspond to $1.1\times10^{16}cm^{-2}s^{-1}$ for 100eV H^+, which is a peak particle load at the first wall of ITER. In experiments with TiC coating on graphite irradiated with a high heat flux plasma (NAGDIS-I plasma) at $1\times10^{17}cm^{-2}s^{-1}$, it has been found that, as the temperature increases the Ti sputtering yield at 180 eV H^+ increases a little gradually, hereafter decreases abruptly at 1000°C and again increases through a deep minimum (~1/3 of the room temperature value) at 1200°C.

Concerning the hydrogen retention it has been shown that the steady state depth profiles of hydrogen implanted into graphite are excellently well reproduced by the solution of the mass balance equations for both freely migrating hydrogen and trapped one, in which relavant elementary processes; diffusion, recession of the surface by sputtering, implantation source, trapping (or retrapping), thermal and ion-induced detrapping, local molecular recombination between activated (free) hydrogen atoms and that between an activated hydrogen atom and a trapped one and hydrocarbon formation leading to methane emission, are taken into account. By best fitting of the solution to the experimental data, the diffusion constant of free hydrogen and the rate constant of local molecular recombination between an activated hydrogen atom and a trapped one are determined as a function of inverse temperature.

In experiments on the MeV He^+ ion-induced re-emission of hydrogen isotope at room temperature it has been found that the re-emission profiles of H and D are excellently well reproduced by the solution of the above mass balance equations at room temperature. From the data analysis the ratios of the rate constants of local molecular recombination between an activated hydrogen atom and a trapped one to trapping have been determined and it has been shown also that there exists a strong isotope effects in the ratios for H and D.

In experiments on the isothermal re-emission of hydrogen implanted up to saturation, it has been found that local molecular recombination between activated hydrogen atoms and hydrocarbon formation play a major role in the re-emission process. From the data analysis the thermal detrapping rate constant, the effective local molecular recombination rate constant and the branching ratio of the hydro-carbon emission to hydrogen molecule emission have been determined as a function of inverse temperature. It has also been found that there exists a strong isotope effect in the effective local molecular recombination rate constants for H and D.

In experiments on the isothermal re-emission of hydrogen implanted at under-saturation levels, it has been found that the re-emission rate becomes smaller as the initial implantation concentration decreases, which is ascribed to retrapping effect of thermal activated hydrogen at available open traps. From the data analysis, the ratio of the rate constants of hydrocarbon molecule formation to trapping has been determined as a function of inverse temperature.

Finally, in order to correspond the data on the elementary processes obtained by direct measurement of hydrogen retained in the target specimen to those by measurement of emitted hydrogen and hydro-carbon molecule, the thermal desorption spectra of them have been calculated from the solution of the mass balance equations. The calculated thermal desorption spectra have been shown to be in good agreement with the experimental ones obtained previously by several authors.

IN THE LAST two (1993, 1994) years, we have performed following two tasks concerning this project: (1) temperature dependence of the metal sputtering yield from TiC coating on graphite by high heat flux plasma irradiations and (2) isotope effect of the hydrogen retention under simultaneous dual ions irradiation.

(1) Temperature dependence of the metal sputtering yield from TiC coating on graphite by high heat flux plasma irradiation

An optical spectroscopy technique for in-situ measurement of the metal sputtering yield from the target by irradiation of high heat flux plasma has been developed at the NAGDIS-I plasma machine.

It has been observed that the temperature dependence of the steady state TiI line intensity for the TiC coating graphite at different He^+ ion impact energies and a flux of $1.2\times10^{17}cm^{-2}s^{-1}$ are very similar to that of the W sputtering yield from the WC coating graphite by 5 keV Ar^+ bombardment. Moreover, time transient Ti sputtering yield increases at the two stages which well corresponds to the theoretical expression of change in the surface coverage of segregated carbon atoms.

There results indicate that the in-situ optical spectroscopy measurement of the transient sputtering yields provides with the rate constants of elementary processes such as segregation, dissolution and diffusion relevant to the self-sustaining coverage with segregated carbon atoms which are important for selection of preferable materials.

(2) Isotope effect of the hydrogen retention under simultaneous dual ions irradiation

For establishment of the recycle model of hydrogen isotopes, the re-emission of H and D implants from graphite by bombardments of D^+ and H^+ ions, of which the peak depths in the target coincide with each other, has been studied by means of the ERD technique. It is found that the decay rate of H implants by the D^+ ion bombardment is larger at the low ion fluences than that of D implants by the H^+ ion bombardment and hereafter the former becomes almost the same as the latter. The decay curves have been analysed by best fitting of the analytical solution of the mass balance equations, in which retrapping, ion-induced detrapping and molecular recombination are taken into account. The detrapping cross-sections of H by 2.0 keV D^+ and D by 2.5 keV H^+ ion bombardments have been determined to be 3.3×10^{-18}cm^2 and 2.5×10^{-18}cm^2, respectively. The isotope effect observed in the detrapping cross-sections is well explained in terms of displacement collision of energetic projectiles with trapped species.

The concentration of H and D atoms retained in graphite at room temperature by simultaneous dual implantation with H^+ and D^+ ions, of which the peak depths in the target coincide with each other, have also been measured as a function of time to establish the recycling model of hydrogen isotopes. It has been found that the relative concentrations of H and D increase in the same way in the beginning, while hereafter separate from each other and the relative concentration of H saturates to a lower level faster than that of D does to a higher level. The ratio of the saturation concentrations of D to H has been found to be 1.8, which is so-called the isotope effect of the hydrogen retention by simultaneous dual irradiation.

The experimental data on the relative concentrations of H and D retained are shown to be very consistent with the theoretical value 1.6, calculated by solving a set of the mass balance equations for H and D, which has been developed from a model for formation of mixed molecule HD and the mass balance equations successfully describing the retention and re-emission of hydrogen isotopes on single ion implantation.

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COORDINATED RESEARCH PROGRAM ON
"PLASMA-INTERACTION INDUCED EROSION OF FUSION REACTOR MATERIALS"

(International Atomic Energy Agency)
Program Duration: 1990-1995

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1. INTRODUCTION

Our research has been focussed on the interaction of plasma-facing materials with plasma particles characteristic of the fusion reactor environment. Here we will concentrate on carbon (in the form of graphite, carbon/carbon composites, and carbon doped with other elements) which is the most extensively used first-wall material in present-day fusion devices, and is also one of the reference materials for the International Thermonuclear Experimental Reactor (ITER). Emphasis has been on the understanding of the mechanisms related to hydrogen transport and erosion processes. The former includes hydrogen diffusion, retention, reemission and recombination; these topics are part of an IAEA Coordinated Research Program on "Tritium Retention in Fusion Reactor Plasma-Facing Components", and will not be discussed here. The erosion processes investigated during the last five years include chemical erosion, synergistic effects in chemical erosion, and radiation-enhanced sublimation (RES). The effect of dopants on these processes was also studied. For the doped graphites, we also measured the thermal diffusivity and conductivity which are critical parameters for high heat flux components in fusion reactors.

2. RESEARCH FACILITIES

The major facilities used in our investigation are two mass-analyzed, low-energy, high-flux ion accelerators. One of the units consists of a single ion beam, while the other unit has two ion beams of independently controllable fluxes and energies. Available ion species include: H^+, D^+, He^+, C^+, O^+, Ar^+, Ne^+, etc. Energies range from ~10 keV down to <100 eV. Typical H^+ flux at 1 keV energy is $\sim 10^{20}$ H^+/m^2s. Recent developments of gaseous divertors have led to prospects of <10 eV edge temperatures in the divertor region. This prompted us to extend our experimental capability to energies down to the 10's eV range, using a mass-analyzed ion gun with a specially designed deceleration stage. Beam currents of ~4 μA on a spot of ~5 mm^2 are obtained at 20 eV D^+ energy (5×10^{18} D^+/m^2s). This unit will be installed in our Tritium Laboratory [20] where erosion experiments with T^+ impact will also be performed. Thermal diffusivity and heat capacity measurements were made using the laser-flash method — with a 40 J neodymium-glass laser (~0.5 ms pulse).

3. CHEMICAL EROSION OF PURE GRAPHITE

When carbon — usually in the form of graphite — is exposed to H^+ or D^+ impact, initially the hydrogen is trapped within a depth corresponding to the range of incident ions. After reaching a certain hydrogen concentration within the ion implantation zone, a transient evolution of the reemission of hydrogen [22] and the formation/release of volatile hydrocarbons is observed [1,14]. In the energy range 50-3000 eV, the dominant hydrocarbon released from pyrolytic graphite (Union Carbide HPG99) is methane [16]. Other hydrocarbons released include C_2H_2, C_2H_4, C_2H_6, C_3H_6, and C_3H_8. At 50 eV the C atoms released in the form of methane is ~50% of the total C atoms released. With increasing H^+ energy, the relative contribution of the heavier hydrocarbons is further reduced — to about 10% of total C erosion at 3 keV. Chemical erosion dominates in the 600-900 K temperature range, with a maximum of ~0.1 $\Sigma C_xH_y/H^+$ at ~300 eV and ~800 K. First results with our new low-energy (10's eV) ion beam show methane yield maxima of ~10^{-2} CD_4/D^+ occurring at temperatures of about 500 K for 10-15 eV D^+ energy [unpublished].

Comparison of the chemical erosion results of an undoped carbon/carbon composite material (AEROLOR A05G, with short fibres randomly distributed in the x-y plane) with those of pyrolytic graphite, shows no significant differences [16]. Also, no significant differences were observed for the two orientations of the C/C material, even though significant differences are seen in the microstructure.

In an attempt to study the mechanisms related to the formation of hydrocarbon molecules in graphite, specimens were simultaneously bombarded with mixed species hydrogen (H^+ and D^+) of independently controlled ion energies, and thus different depth distributions [9]. By monitoring the reemitted CH_xD_y molecules, information was obtained on the mechanism and spatial origin of the methane formation process. By changing the depth distribution of the two impacting species (H^+ and D^+) from "complete overlap" to "total separation" the amount of mixed CH_xD_y molecules was observed to decrease [9,12], supporting the end-of-range methane molecule formation hypothesis [Vietzke et al, J.Nucl. Mater.128/129(1984)545; Roth and Bohdansky, Appl.Phys.Lett.51(1987)964]. Furthermore, the transient behaviour of the methane formation rate indicates the breakup of methane molecules as they diffuse to the surface to be released [7,8].

In fusion reactors, the released C atoms and C-containing molecules/radicals will be redeposited, in combination with the fuel H, on the surfaces of plasma-facing materials. This process is referred to as "codeposition", and the resulting surface material is an amorphous hydrogenated carbon film (a-C:H). From safety considerations, it is of interest to study the stability of such codeposited layers due to exposure to atmosphere. Of special interest is the form of the released hydrogen (tritium in D-T burning reactors) during atmospheric exposure. With these issues in mind, we performed experiments where codeposited a-C:D and a-C:H films were exposed to oxygen at 520 K. Results show that over 99% of the released hydrogen is in the form of water, while < 1% is released as D_2 or H_2 [5]. No apparent methane production was detected [5]. The main C-containing reaction products were CO and CO_2. XPS and SIMS analyses of the films indicated the appearance of carbonyl groups and an increase in the concentration of hydroxyl groups due to surface oxidation. The generally accepted scheme for simple thermal oxidation of hydrocarbon polymers was used to provide a plausible reaction mechanism leading to emissions of the reaction products D_2O, CO_2 and CO.

4. SYNERGISTIC CHEMICAL EROSION OF GRAPHITE

Previous chemical erosion studies, using one energetic species (e.g., H^+, Ar^+) in combination with thermal H^o have shown the existence of a synergistic effect, leading to an enhancement in methane formation [e.g., Haasz, Vietzke et al, J.Nucl.Mater.145-147(1987)412]. An obvious reactor-relevant extension to this study was to use energetic C^+ (plasma impurity) and H^o and H^+ (fuel atoms/ions). For the case of C^+/H^o, we have found that thermal H^o, in combination with energetic C^+, results in chemically enhanced self-sputtering of carbon in the 600-900 K temperature range [15]. Experiments with H^+ and C^+ were undertaken to study the effect of H^+ energy on the erosion enhancement. We found that the addition of C^+ (1-3 keV) to H^+ with >300 eV energy does not appear to enhance the erosion yield above the level obtained for H^+ alone [13], indicating that all of the hydrogen was used up in stabilizing the ion-induced damage in the near-surface layer. The additional damage by the C^+ does not appear to lead to significantly more hydrocarbon formation due to the limited supply of H. When in combination with 100 eV H^+, the C^+ are able to enhance the hydrocarbon formation rate through the production of additional suface damage. Thus the hydrocarbon formation yield due to H^+ ions with <300 eV energy (including thermal H^0) may be increased to the level corresponding to ~300 eV H^+, where the H^+-induced chemical erosion yield is at its maximum.

To investigate the effect of energy deposition into the near-surface layer of graphite, we also studied combined exposures of H^+/He^+ [13], H^+/Ar^+ and H^+/Ne^+ [10]. The addition of He^+, Ne^+, and Ar^+ to H^+ is also of interest from a fusion reactor point of view. The He, being the ash of fusion reactions, will be present in the plasma edge together with the H fuel. Introduction of Ne and Ar into the edge plasma, on the other hand, has been considered in order to reduce the plasma temperature and thus reduce wall erosion. Of course, one must also consider the erosion enhancement due to the presence of these species. It appears that in all cases the energy deposition due to the non-hydrogenic species will enhance the erosion yield of <100 eV H^+ ions (or thermal H^0) to that of 300 eV H^+.

Experiments were also performed in order to assess the effect of electrons, in addition to H^+ ions, on the formation of hydrocarbon reaction products. This work was done in collaboration with Vietzke et al, KFA, Julich. Essentially, no effect on hydrocarbon formation was observed in the temperature range 800-2000 K [17].

5. RADIATION-ENHANCED SUBLIMATION OF GRAPHITE

For temperatures above 1200 K, the erosion yield of graphite (and carbon-based materials) during energetic ion impact increases monotonically with increasing temperature. The effect occurs for hydrogenic as well as non-hydrogenic and chemically inert incident particles. Most of the experimental features of RES (e.g., energy and temperature dependence) can be explained by a model which describes the process as the sublimation of interstitial carbon atoms which are created by the incident energetic particles. However, the experimentally measured flux dependence [4,6,18; also Haasz and Davis, J.Nucl. Mater.151(1987)77; Philipps et al, J.Nucl.Mater.155-157(1988)319] does not support the model predictions. We have performed new RES measurements using a line-of-sight mass spectroscopy technique. The quadrupole mass spectrometer was modified to block the transmission of reflected beam ions and physically sputtered C atoms, thus enabling us to extend the temperature range of our RES measurements to ~400 K. We investigated the dependence of RES on graphite structure as well as ion flux density. The RES yields were found to depend on both the type and orientation (for non-isotropic graphite) of the specimens [6]. The highest yields are associated with the most dense and most ordered graphite (pyrolytic graphite, HPG99, from Union Carbide); ~0.2 C/D at 1800 K for 1 keV D^+. The yield at 400 K is of the order of 10^{-3} C/D for 1 keV D^+, more than one order of magnitude lower than the physical sputtering yield. Our new flux dependence results [4] agree with our previous results and those of Philipps et al [see above refs.]. The model predicts a RES flux dependence to the power of about (-0.25), whereas the experiments show a power of about (-0.1).

6. EROSION OF DOPED GRAPHITE

Our research on doped graphites involved a comprehensive assessment of the effect of dopants and their concentrations on four key fusion-relevant performance parameters: chemical erosion, RES, hydrogen transport/reemission, and thermal conductivity. While thermal conductivity is not an erosion process itself, the material's ability to handle high-flux power loads will have an impact on the material's temperature, and consequently on its erosion behaviour. Our results on thermal conductivity can be found elsewhere [21]. Our work on hydrogen transport/reemission forms part of the IAEA Coordinated Research Program on "Tritium Retention in Fusion Reactor Plasma-Facing Components", and will not be discussed here.

6.1 Mechanical and Thermal Properties of Doped Graphite

Doped bulk graphite specimens were specially fabricated for our experiments by Ceramics Kingston Caramique (CKC). Dopants included B, Si, Ti, Al, Ni and W. Mechanically, most of the specimens were somewhat brittle. The Al-doped graphite, after several months of air exposure at room temperature, completely pulverized. We also experienced difficulty with the Ni-doped specimens; above 1000 K molten Ni was found on the specimen surface. Thermal diffusivity measurements revealed that the CKC specimens were anisotropic [21]. For the undoped reference material, the thermal conductivities in the two directions, parallel with and perpendicular to the planes, were 140 and 20 W/mK at 500 K, respectively. The effect of dopants in the low-conductivity direction was negligible. In the high-conductivity direction, however, the conductivity was found to decrese — more so at low temperature, resulting in a reduced temperature dependence. In brief, for the 10-20% dopant concentrations, where improvements in chemical erosion and RES were observed (see below), thermal conductivities in the high direction are slightly lower than the well-known isotropic (Ringsdorff) EK98 graphite.

6.2 Chemical Erosion of Doped Graphite

As noted above, the maximum chemical erosion yield of pure graphite, when exposed to H^+ ions, is ~0.1 $\Sigma C_xH_y/H^+$ at ~300 eV energy and ~800 K temperature [16]. For comparison, the corresponding chemical erosion yield for sintered boron carbide is about two orders of magnitude lower [19]. Doping of graphite leads generally to reduced hydrocarbon formation, relative to pure graphite, during H^+ irradiation. Methane yield reductions, relative to pyrolytic graphite, were observed to be most pronounced at temperatures $>T_m$ [2,11]. Largest yield reductions, as high as a factor of 5, were seen for the B-doped specimens (~8 at% surface concentration); somewhat less reduction (up to a factor of 2) was observed for specimens with ~4-5 at% Ti or Si and ~1 at% W surface concentrations [2]. Some dependence of chemical erosion yield on specimen orientation was observed.

Also related to chemical erosion is the safety concern for fusion reactors containing large amounts of "hot" graphite when exposed — possibly by accident — to oxygen (i.e., via air exposure). Threfore, in addition to the need to reduce graphite's chemical reactivity to H^+, we also need to reduce its reactivity to oxygen. We have performed erosion experiments on the CKC specimens at temperatures of ~1000 K in air. Again, the B- and Ti-doped specimens were observed to provide the best resistance to carbon oxidation [2]. Specimens with ≥8 at% B and ~5 at% Ti surface concentration were found to resist erosion for temperatures as high as ~1100 K. For the Si- and Ni-doped specimens, erosion in air at ~1000 K was similar to the case of the undoped reference material. The W-doped specimen, on the other hand, underwent rapid oxidation (exothermic) causing the material to disintegrate [2].

6.3 Radiation-Enhanced Sublimation of Doped Graphite

Our experiments with the CKC doped materials show that RES can be reduced by doping pure graphite with B, Si or Ti. Generally, with few exceptions for small dopant concentrations, the RES yields decrease with increasing dopant concentrations, more or less independent of the dopant element. For surface concentrations of more than 10-15 at% B or 2-5 at% Ti, the RES yield is reduced by a factor of 3-4, compared to the yield for an undoped specimen, at 1800 K for 1keV D^+ irradiation [3]. As in the case of chemical erosion, different RES behaviour is observed for the different graphite orientations. The physical processes which govern RES of doped graphite are still not understood. RES is influenced not only by the dopant element itself, but by the graphite structural changes caused by the doping and manufacturing processes.

7. SUMMARY

The main erosion processes for carbon in a fusion reactor environment, under normal operating conditions, are: (i) physical sputtering caused by all species of energetic particles, occurring at all temperatures for incident particle energy above an energy threshold; (ii) chemical erosion, dominating in the 600-900 K range for incident H^+ energy >50 eV, and at lower temperatures for <50 eV; (iii) radiation-enhanced sublimation, becoming important above ~1200 K, and produced by all species of energetic particles; and (iv) thermal sublimation above ~2000 K. Emphasis in this work was on chemical erosion and RES, and the effect of doping pure graphite on these processes.

7.1 Chemical Erosion and Synergistic Chemical Erosion

Chemical erosion due to H^+ irradiation is dominated by hydrocarbon formation in the 600-900 K temperature range. Methane is the dominant hydrocarbon for H^+ energy >50 eV. The contribution of heavier hydrocarbons increases with decreasing energy. The hydrocarbon yield, as a function of temperature, is characterized by a maximum (~0.1 $\Sigma C_xH_y/H^+$ for 300 eV H^+) at ~800 K. The chemical erosion of various forms of graphite, including carbon/carbon composites, was found to be similar. First results for D^+ energies <50 eV show reduced yields and a shift of the location of maximum to lower temperature. For 10-15 eV D^+ the maximum yield is ~10^{-2} CD_4/D^+ and T_m is ~500 K.

If H^+ is combined with non-hydrogenic, non-reactive energetic species, the hydrocarbon formation rate may be enhanced, with the level of enhancement depending on the energies of the impacting particles. For <100 eV H^+, in combination with 1 keV non-hydrogenic species, the yield could be increased to levels corresponding to the maximum yield obtained with H^+ alone at ~300 eV H^+.

In a fusion reactor, the eroded C atoms and the H fuel lead to the production of codeposited films, which in turn will be exposed to the fusion plasma. Results (not reported here) show that the erosion behaviour of such films is similar to that observed with pure graphites, the reason being that H^+ impact on pure graphite will in fact result in the formation of a similar film — an amorphous hydrogenated carbon film (a-C:H). What happens when such films are exposed to oxygen, for example, during an accidentalal vacuum loss? More than 99% of the hydrogen (tritium in a D-T burning reactor) from the codeposited layer is released in the form of water.

7.2 Radiation-Enhanced Sublimation

Our RES results for pure graphites show that the RES yield depends on the graphite structure and orientation in the case of non-isotropic graphite. The highest yields are associated with the most dense and most ordered graphite (~0.2 C/D at 1800 K for 1 keV D^+). The yield at 400 K for 1 keV D^+ is of the order of 10^{-3} C/D, more than one order of magnitude lower than the physical sputtering yield. Experimental flux dependence results show that the RES yield varies as the flux to the power of ~(-0.1), in disagreement with model predictions of a power of ~(0.25).

7.3 Erosion of Doped Graphite

The doped CKC material was found to be anisotropic vis a vis thermal conductivity. We also found the hydrocarbon and RES yields to depend on the specimen orientation. Both the hydrocarbon and RES yields were reduced by doping. Generally, both yields were seen to decrease with increasing dopant concentrations. Largest chemical yield reductions, up to a factor of 5, were seen for the B-doped specimens, with somewhat less reduction (up to a factor of 2) seen for the Ti-, Si- and W-doped specimens. The largest RES yield reductions, a factor of 3-4, were seen for the B- and Ti-doped material. Similarly, the B- and Ti-doped specimens were found to resist erosion in air at temperatures as high as ~1100 K. Based on these results, B and Ti have emerged as the two most promising elements for reducing the erosion of graphite under plasma (chemical and RES) and air exposure.

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Summary of the RCP "Plasma-interaction Induced Erosion of Fusion Reactor Materials" at IPP-Garching

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1. Physical Sputtering

A comprehensive collection of sputter yields measured and calculated over the years at IPP in Garching has been published [1]. Most data are for normal incidence but also many data are given for the angle of incidence dependence. This data collection lead to a revision of the Bohdansky formula for the sputter yield at normal incidence [2]. The essential point was the replacement of the nuclear stopping based on the Thomas-Fermi potential by a nuclear stopping formula based on the KrC potential which gives a more realistic description of atomic collisions at low energies. In addition a new empirical formula for the threshold energy of sputtering was given. It was also shown that the Yamamura formula for the angular dependence of the sputter yield cannot be applied at low energies and for small mass ratios (target mass to projectile mass). A simple model explains why the threshold energy is dependent on the angle of incidence for low mass ratios [3]; the important point is the inelastic energy loss which limits the number of collisions. This paper also reviews the earlier literature on the topic.

Computer simulation is an important tool for producing sputtering data. The physical and computational methods are described in a book [4]. Typical results are shown in [5]. The threshold behaviour of sputtering is studied for the cases D, Ar, Cu on Cu and Xe on C to cover a large mass ratio range [3]. The influence of the interaction potential used in simulations is discussed extensively for Si selfsputtering [6]. The largest deviations in yield occur for grazing incidence between purely repulsive and repulsive + attractive potentials.

Computer simulation with the binary collision program TRIM.SP (version TRVMC) is applied to create sputtering yield and sputtered energy data for energies up to 1 keV (10, 12, 15, 20, 25, 30, 50, 70, 100, 140, 200, 300, 500, 1000 eV) and 9 angles of incidence (0, 15, 30, 45, 55, 65, 75, 80, 85 degrees). The number of incident angles and the values are fixed; the number of incident energies is chosen so that the lowest yields given are about 10^{-5}, still lower values are put to zero. The data are given in the form of matrices (fixed energies in lines, fixed angles of incidence in columns). Similar matrices are determined for both particle and energy reflection coefficients. The matrices are stored at /afs/ipp/u/wge/trim.data/sputter.data and refl.data. So far, matrices for H, D, T, C, N, Ne, and Ar on C have been produced.

The sputter yields of the refractory metals Mo and W by D and T as well as selfsputtering are calculated as function of incident energy and angle [7]. Data are also provided for a Maxwellian distribution of the projectiles. Similar data are determined for the metals Li, Ga, and In which are liquid at relatively low temperatures and can be regarded as wetting materials for the first wall [8]. A figure of merit clearly shows the advantages and disadvantages of low and high Z materials.

The angular dependence of the selfsputter yield of Be was determined experimentally and by simulation [9]. The lower experimental yields at large angles of incidence compared to the calculated values are explained by the rough target surface. A review of 'Properties of Beryllium as a Plasma facing Material" gives sputter yields for D, T, and Be ions and a Maxwellian distribution besides data on trapping and heat conductivity [10].

The energy and angular dependence of the sputter yield of B and B_4C is investigated experimentally and by computer simulation [11]. SEM micrographs give an impression of the surface topography before and after irradiation.

The influence of surface roughness is clearly demonstrated experimentally for the bombardment of graphite by D and C [12]. In general, surface roughness has the effect of increasing the sputter yield at normal incidence and of decreasing the yield at oblique incidence (larger than 45°). The decrease at the sputter yield maximum was found to be a factor of 5 between a well polished surface and the most rough graphite (POCO). Good agreement between experimental data and computed results are found for the best polished surface (pyrolitic graphite).

Energy distributions of positively and negatively charged carbon ions sputtered by 5 keV He, Ne, Ar, and Kr at oblique incidence have been measured [13]. Comparison with calculated distributions show reasonable agreement. The negative fraction of the sputtered carbon is larger than the positive fraction.

Ni selfsputtering is compared with the sputtering of Ni with Kr [14]. Experimental results clearly establish the effect of the planar surface binding effect (acceleration and refraction of the projectile) for oblique incidence as predicted by computer simulation. Experimental and calculated values for the sum of the sputter yield and the particle reflection coefficient versus the angle of incidence are given for the selfbombardment of Ni.

Isotopic fractionation by ion bombardment is studied with the system Ar on $Mo^{92}_{0.5}Mo^{100}_{0.5}$ by computer simulation [15]. The fractionation is larger than expected from Sigmund's theory; the reason is the influence of primary knockon atoms which are only a small fraction but show a much larger fractionation than the main part of cascade atoms (secondary knockon atoms). The effect on the energy and angular distribution of sputtered atoms is discussed.

2. Temperature dependent erosion

Temperature dependent erosion is investigated for the sputtering of W by O and OH up to 1900K in the energy range from 150 eV to 10 keV [16]. The yield increases with temperature, especially at low projectile energies.

The temperature dependent behaviour of doped graphites and B_4C is discussed in [17]. The erosion yield for 1 keV D is given for 300, 800, and 1470 K to show the effect of chemical erosion and radiation enhanced sublimation. The erosion of low-Z materials are compared in [13] and for carbon-based materials in [18].

Chemical erosion of pyrolytic and boron doped graphite (USB15) is still present at low D energies (down to 10 eV) and low temperatures (300 K) [19]. B diffusion and release in USB15 is measured by nuclear reaction analysis and Auger spectroscopy at high temperatures (up to 2000 K) [20]; in addition, erosion under 1 keV D bombardment at this high temperature is determined.

Sputtering and surface composition modifications of Ti doped graphite (RG-Ti) due to 50 eV to 1 keV D bombardment is studied at temperatures up to 2000 K [21]. D

trapping and release is investigated too.

A formula for the chemical erosion of graphite is given for the temperature range from 300 to 1200 K and bombarding hydrogen energies from 1 eV to 10 keV [22].

The deposition of hydrogenated carbon layers on graphite and silicon by energetic CH_3 ion beams is studied up to 1000 K and as a function of fluence [23]. A further study deals with sputtering and segregation of Cu/Li alloys [24]. This paper reviews also the literature about this special system.

3. Multicomponent Systems

The sputtering of W by C is investigated experimentally and by computer simulation. It is shown that for normal incidence C deposition on W is found, whereas for grazing incidence sputtering prevails. The deposition regime switches over to an erosion behaviour at an angle of incidence of about 40°. With larger incidence angles the C concentration decreases and the equilibrium conditions are reached at lower fluences [25]. The system C on Be is investigated in [26]. Other systems are given in [27].

The sputtering of C, Si, and W by the simultaneous bombardment of a Maxwellian distribution of D and C is modelled with the dynamic Monte Carlo program TRIDYN. The impurity concentration of C in the incident flux determines strongly, if C is deposited or if the target is eroded. The occurrence of erosion or deposition also depends on the fluence. An analytic model allows to describe the general behaviour [28].

3. Trapping

The trapping of D in grahite (EK98 and HOPG) is studied in [29-31]. It is shown that at low energies some of the implanted amount is lost even at low fluences which is not the case at energies above 500 eV [30]. The damage in HOPG is determined by Rutherford backscattering [31]. From the trapping measurements the particle reflection coefficient is gained as a function of the incidence angle [29,30]. New datasets for the reflection of D and He from W, T and He from Fe are provided in [32].

Oxygen retention in B_4C and B-doped graphites irradiated by D is discussed in [33],

He trapping and radiation damage in graphites [34,35].

Thermal desorption and reemission of D_2 and CD_4 from B_4C and boronized graphits is investigated in several papers [36-38]. Another paper deals with time-resolved measurements of the hydrogen inventory in graphite under plasma exposure [39]. [40] evaluates Si doped CFCs as a plasma facing material.

4. Review articles

Review papers on physical sputtering [41], erosion of graphite due to particle impact [42], reflection [43], and trapping, detrapping and release of implanted hydrogen isotopes [44] are provided.

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Final Report on the Research Project # 6237/CF IAEA-KFA Jülich "Chemical Sputtering and Radiation-Enhanced Sublimation of Fusion Reactor Materials"

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The work in this project was performed using ion beam experiments and in-situ experiments in the tokamak TEXTOR. The names of contributors may be taken from the reference list. The results are summarized in this report and are discussed on whether or not they are sufficient for modelling erosion behaviour.

1) Chemical erosion of carbon-based materials under energetic oxygen beam irradiation

A sufficient database exists on the oxygen erosion of carbon and boron-doped carbon under energetic beam irradiation with respect to the total erosion yield as function of energy [1], the oxygen retention [2], the spectrum of released products [2-4] and the energy distribution of the released products[4]. Some of the results are mentioned here, up to about 1200 K the reaction of O^+ with carbon and boron-doped carbon leads mainly to the formation of volatile CO and CO_2 together with physically sputtered carbon, boron and boron oxide species. For the case of carbon, the total chemical erosion yield is about 0.6 eroded C/incident O^+, nearly independent of temperature and energy over a wide range of energy (50 eV to 3 keV) and temperature. The retention of oxygen in graphite within the implantation zone is 0.25 O/C. Compared to graphite, the retention of oxygen in B-doped carbon is higher (depending on the boron content) and the reemission of CO and CO_2 is stronger but delayed after starting the bombardment which partly explains the success of the "boronization" procedure of tokamaks.

2) Chemical erosion of carbon-based materials in the plasma edge of TEXTOR

A large database exists for the hydrocarbon formation from carbon and carbon-based materials under hydrogen ion irradiation (see Final Report by A.A.Haasz). An extrapolation from the ion beam data to plasma edge conditions (low energy, high flux density) is difficult. Thus, an in-situ determination of hydrocarbon formation under plasma edge conditions has been performed in TEXTOR by two different methods: i) in-situ mass spectrometry (Sniffer probe) [5] and, ii) optical spectroscopy in front of a test limiter [6]. Hydrocarbon formation has clearly been seen in both methods and also a decrease of the methane formation with increasing flux density. Unfortunately, a consistent database for the hydrocarbon formation under fusion edge plasma conditions could not be obtained. Sniffer probe data are three times lower for the methane formation than optical measurements; they show a clear maximum at 800 K whereas optical measurements results in a constant methane formation yield of 0.03 CD_4/D up to temperatures of 1100 K, followed by a decrease above this temperature. Sniffer probe data for higher hydrocarbon formation have also been obtained. The C_2D_x is formed with the same yield as CD_4 and C_3D_x with a ten times smaller yield with both yields increasing with decreasing plasma temperature as in ion beam experiments. This high yield means that the higher hydrocarbon formation dominates the chemical erosion of carbon. After the siliconization of TEXTOR the methane formation yield is reduced only by a factor of two, whereas the higher hydrocarbon formation is suppressed by a factor of ten.

3) Active control of erosion and deposition on limiters/divertors

The lifetime of limiter/divertor components depends on the balance between erosion and redeposition. In-situ colorimetry [7] has been successfully applied in TEXTOR to study erosion and redeposition on extended areas [8]. Code calculations [9] show that local processes (transport) near the surface are important for these processes. The main goal of these erosion studies is to understand and predict the net erosion behavior of plasma-facing components in a steady state reactor. A further step is the development of in-situ methods to control the erosion and deposition. First attempts have been made by using reactive gas puffing through limiter surfaces which leads to layer deposition in erosion dominated zones [10,11].

4) Radiation-enhanced sublimation (RES)

A sufficient database exists for the yield, the spectrum and energy distribution of emitted particles of radiation-enhanced sublimation by ion beam impact on carbon materials [12,13]. Furthermore, no strong flux density dependence ($F^{-0.1}$) is observed up to 5×10^{19} Ar^+ or H^+/m^2s, a stronger decrease of the yield with increasing flux density ($F^{-0.26}$) may be possible above 10^{20} Ar^+/m^2s [14]. Completely different is the situation under edge plasma conditions in tokamaks. RES seems to play only a negligible role [15]. No drastic enhanced carbon atom emission is seen in TEXTOR, JET and TFTR with increasing temperature of the carbon material above 1000 K. Tore Supra claims to see RES but the spatial resolution of the temperature measurement is only 1 cm^2 and hot spot formation cannot be excluded which may lead to normal thermal sublimation. Thus, further experiments will be performed in TEXTOR with an externally heated carbon limiter which allows study of the flux density dependence of RES under plasma exposure.

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Summary of materials erosion and redeposition research for 1990-1995 for the development of plasma-facing components in ITER

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Abstract

Materials erosion and redeposition is widely recognized as a critical issue in developing plasma-facing components for existing and future magnetic fusion devices. To address and resolve this critical issue, experimental research has been conducted using the PISCES-B facility at UCLA (and UCSD). Over the last five years (1990-1995) beryllium, carbon and tungsten materials have been evaluated as divertor candidate materials for ITER, with respect to their erosion and redeposition characteristics. This report summarizes the work for this period during which four research coordination meetings took place at IAEA.

1. Introduction

For the ITER plasma-facing component application, candidate materials must meet a wide range of requirements. There are only three candidates that are believed to be qualified for this application, i.e., beryllium, carbon and tungsten. In Table 1, these candidates are compared with respect to some of these requirements. As can be seen, there is no single perfect material for the ITER divertor application. In the PISCES program we have evaluated these three candidates from the erosion and redeposition point of view.

Table 1 Fusion-related properties of the candidate materials for ITER divertor applications [1].

Preferred Properties	Beryllium	Carbon	Tungsten
Low atomic number	4	6	74
Low sputtering yield (by D^+ at 100 eV at 50°)	0.12	0.02	0 1)
High melting point (°C)	1283	3367 2)	3410
High thermal conductivity (W/m K)	300	50-800 3)	180
High heat capacity (J/g K)	2.3	1.6	1.4
Large electron impact ionization rate coefficient (cm^3/s) 4)	5.9×10^{-8}	4.2×10^{-8}	5.5×10^{-7}
Hydride formation or hydrogen co-deposition ?	Yes 5)	Yes	No
Machinable/weldable/plasma-sprayable	Yes/Yes/Yes	Yes/No/No	No/No/Yes

(1) Threshold energy for sputtering of tungsten by deuterium is 347 eV, calculated from Yamamura's formula.
(2) Sublimation temperature for a 1 atm equilibrium vapor pressure.
(3) Room temperature values. Data strongly depend on the structure.
(4) 1st ionization rate coefficient calculated with Lotz's formula for Te = 20 eV. In general, one expects less penetration of sputtered atoms into the core plasma for a larger ionization rate coefficient.
(5) Only several reactions using beryllium compounds have been reported to form BeH_2. Although thermodynamic data indicate the possible formation of BeH_2 in the presence of atomic hydrogen, the direct reaction has not been reported to date.

2. Results and discussion

2-1. Graphite materials research

Graphite materials are used for plasma-facing components in many present-day fusion devices. However, it is also true that graphites have several weaknesses such as chemical sputtering and radiation-enhanced sublimation. Therefore, for the period 1989-1991 we conducted materials development and evaluation campaign jointly with a Japanese graphite manufacturer (Toyo Tanso).

Jointly developed were boronized graphites with boron concentration ranging from 1% to 30% [2]. As shown in Fig. 1, data clearly indicated that chemical sputtering and radiation-enhanced sublimation is significantly (a factor of 3 or so) suppressed for these boronized graphites, relative to that for ordinary graphite and the mechanism for reduced erosion were described in detail [3, 4]. Based on these data, a 20% boronized graphite (GB-120) was chosen as the limiter material for the Wedelstein-7 AS stellarator at IPP-Garching in 1991[5].

However, the weakness of boronized graphites is their low thermal conductivity, meaning that the application of them for long-pulse machines is questionable. Therefore, boronized C-C composites were also developed by distributing boron carbide powder in the matrix volume of composites. Interestingly, data did not indicate any improvement (see CCB-407 data in Fig. 1), regarding plasma erosion resistance [3,4]. The explanation is that boron must be in the solid solution phase uniformly. Therefore, individual carbon-fibers need to be boronized. However, this requirement is difficult to be met because boronization will unavoidably make fibers brittle, affecting the manufacturing process. Also, this will reduce the thermal conductivity. This dilemma is yet-to-be-overcome.

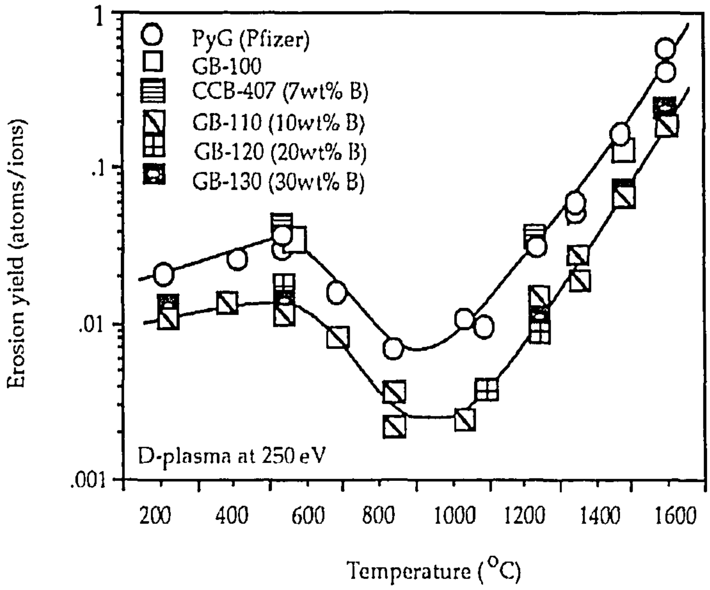

Fig. 1 Erosion behavior of boronized graphite and C-C composites under deuterium plasma bombardment in PISCES-B [3].

2. Tungsten materials research

The PISCES program was directed towards high-Z materials research in 1992-1993. The main emphasis was on the evaluation of tungsten materials, including HIP-bulk (hot isostatic pressure) materials, CVD-coatings (chemical vapor deposition) and LPPS-coatings (low pressure plasma spray).

As shown in Table 1, tungsten has high threshold energies and thus low sputtering yields. The issues to be addressed were whether this is true with coatings and the effect of impurities such as oxygen on the overall erosion. Although the "nominal" oxygen concentration in the DT plasma in ITER is only 0.1 %, tungsten oxide is known to be volatile at temperatures above 1000°C. Unfortunately, this is the operational temperature range of the tungsten divertor (with an open geometry), considered in the CDA (Conceptual Design Activity) phase of ITER.

As shown in Fig. 2 [6], data taken at 1500°C clearly indicated that there is no difference in erosion behavior for bulk-material, CVD-coatings (1mm thick) and LPPS-coatings (1mm thick). The oxide formation and its effect on erosion was found negligible. However, the effect of physical sputtering by oxygen-containing impurities such as H_2O and fragment ions is found to be significant in determining the overall erosion behavior at energies below the threshold for deuterium sputtering.

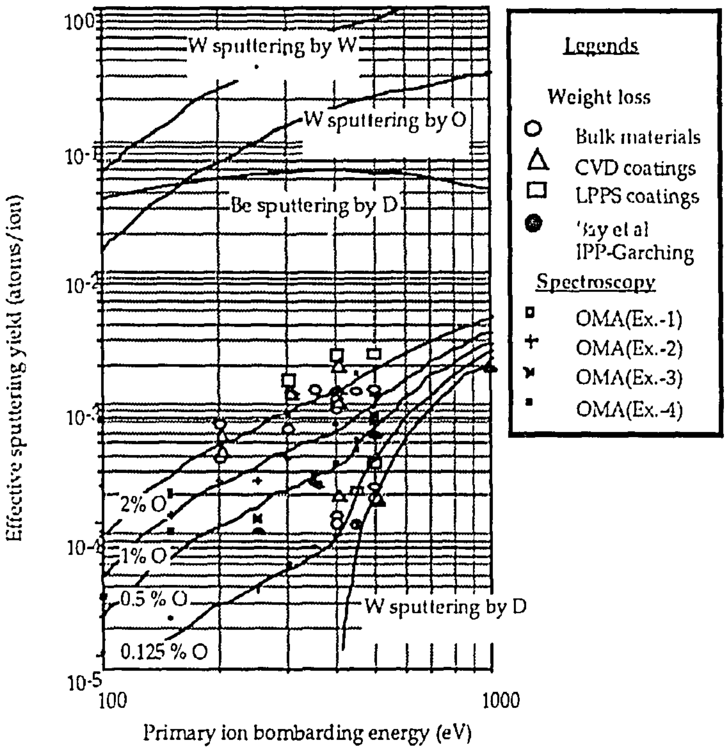

Fig. 2 Tungsten erosion under deuterium plasma bombardment with oxygen contamination [6].

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2-3. Beryllium materials research

Due to the fact that beryllium is a hazardous material, we must build a special facility and come up with special operation procedures. Also, these must be approved by the local EH&S authority. This process took us about a year or so at UCLA. In 1994, we finally started beryllium erosion experiments. By this time, beryllium was chosen as the prime candidate for the ITER plasma-facing components. Therefore, the data from our experiment are to make critical contribution to the EDA(Engineering Design Activity) phase of ITER.

As shown in Fig. 3, data from PISCES experiments indicated high sputtering yield, several orders of magnitude higher than that of tungsten, as predicted by theories and models. This leads to extremely short lifetime of beryllium, i.e., 6.5 hours for a gas-bag divertor [1]. These data strongly discourage the use of beryllium for ITER. In fact, the latest divertor cassette design employs components made of not only beryllium but also carbon and tungsten to resolve the heat load and erosion issues.

However, in the PISCES experiments we found an interesting phenomenon that beryllium tends to be contaminated with trace amounts of carbon-containing impurities such as hydrocarbon molecules and fragments at elevated temperatures, leading to the formation of carbonaceous films. This phenomenon is referred to as "carbon poisoning". Interestingly, carbon poisoning suppresses beryllium erosion because of its shielding effect. First-order modeling has successfully been done and the mechanism is considered to be competitive erosion and trapping followed by intermixing of beryllium and carbon via diffusion [7].

These findings warrant urgent materials compatibility research for beryllium, carbon and tungsten in order that the multi-material divertor design can be evaluated. Currently, this compatibility analysis is under way using the same model for other cases such as beryllium poisoning and tungsten poisoning.

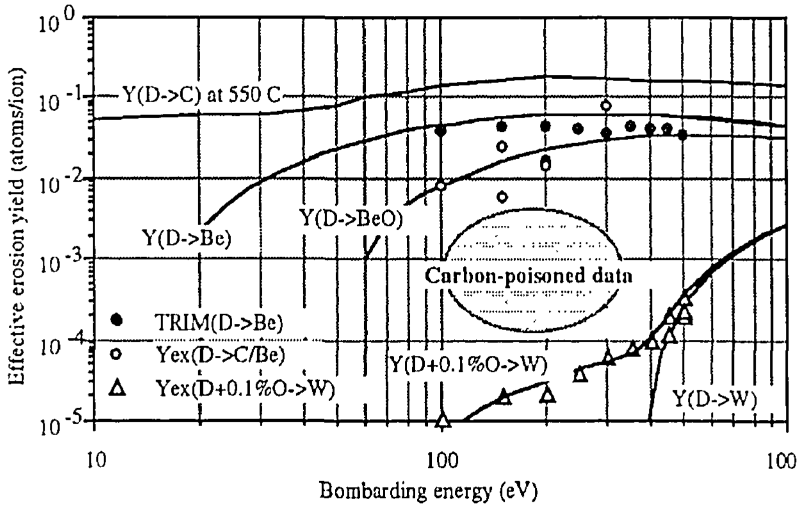

Fig. 3 Erosion data on beryllium, carbon and tungsten under deuterium bombardment in the energy range from 10 to 1000 eV. For beryllium, TRIM calculation results are shown for comparison. Notice that carbon-poisoning can reduce beryllium erosion but not as much as to the level of tungsten [1,7].

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